INCLUSION OF CONSTRUCTION AND DEMOLITION WASTE AS A COARSE AGGREGATE AND A CEMENT ADDITION IN STRUCTURAL CONCRETE DESIGN

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Abstract

Dissociating economic growth from the use of natural resources is imperative to the sustainable development of the construction industry. The use of secondary raw materials by processing and managing construction and demolition waste (C&DW) is one of the major challenges to transition to a circular economy. This study assessed the effect of simultaneously using cement additioned with the ceramic fraction of C&DW and recycled mixed aggregate (RMA) in concrete manufacture by analysing fresh concrete workability, density and air content and mechanical properties of concretes. Regression and variance analyses were run on the findings to determine the effect of RMA and cement type and their interaction on the dependent variables. The percentage of RMA was observed to be the most significant determinant for concrete density and air content. Early age compressive strength was impacted by cement type, although strength in the later age materials was comparable to that of concrete manufactured with conventional cement. The combined effect of cement type and percentage of RMA appeared to have no significant effect on tensile or flexural strength. The findings showed that concrete performance was not substantially compromised by using C&DW-additioned cement and up to 50 % RMA in its manufacture.

Keywords: *construction and demolition waste, recycled mixed aggregate, supplementary cementitious materials, performance, recycled concrete.*

1. INTRODUCTION

The growing concern over the rise in waste generation, the depletion of non-renewable natural resources and ever more damaging pollution is driving governments the world over to reinforce environmental policies geared to mitigating these problems. One such policy, recycling, reusing and valorising waste as an alternative source of raw materials, is a priority target for sustainable growth in developed societies.

The construction industry presently consumes 50 % of all the natural raw materials extracted, generates up to 40 % of anthropogenic waste and emits 30 % of all polluting gas (CO₂) [1-3]. The 859.5 million tonnes of construction and demolition waste (C&DW) generated yearly in the EU alone [4] constitute the largest flow of discarded materials Europe-wide. That waste contains around 54 % by volume of fired clay-based, also called ceramic, materials [5]. Many EU countries are striving to reach 70 % valorisation of such waste by 2020 [6]. According to the latest European Commission report [7], 20 Member States claim to have already met that goal, although their data may include materials used in landfills to regenerate the landscape in excavated areas or for landscape engineering, activities that form part of the objective. Such practices neither maintain the value of those materials in the economy, however, nor contribute to the circular economy, an essential vehicle to meeting the Agenda 2030 Sustainable Development Goals [8]. The industry is nonetheless transitioning to more sustainable development to balance economic growth, the environment and social welfare. For decades, under the leadership of

1 cement and concrete manufacturers, it has mined industrial waste, including C&DW, for alternative raw
2 materials to be used either as additions in cement or aggregate in concrete.

3 C&DW is presently processed at management plants that produce so-called recycled aggregate.
4 Depending on their content, these materials are classified as recycled concrete aggregate (RCA),
5 recycled ceramic aggregate (CA) or recycled mixed aggregate (RMA). RCA has been widely researched
6 in recent years to determine the viability of its reuse in the construction industry, in particular in
7 connection with concrete manufacture [9]. In the wake of the host of papers published on its potential
8 as a coarse aggregate in structural concrete [10-16], it has been included as a new raw material in
9 structural concrete legislation in several countries [17-20]. Much less is known about CA (fired clay-
10 based materials such as brick, roof tile, block and sanitary ware) and RMA, due to the heterogeneity of
11 these materials, RMA in particular. The number of studies in the international literature on the use of
12 RMA in concrete is small compared to the research on RCA, despite the volume of such waste, which
13 in countries such as Spain amounts to 70 % of the total C&DW [21]. Some authors, including Cantero
14 et al [22], Medina et al. [23-26], Martínez et al. [21], Mas et al. [27, 28] and others [29-31] have
15 endeavoured to fill the scientific-technical lacunae in the understanding of these materials. Cantero et
16 al. [22] found that neither compressive nor flexural strength varied significantly at replacement ratios of
17 under 50%. Medina et al. [24] concluded that while exhibiting 18 % lower strength than conventional
18 concrete, materials with up to 50 % RMA are apt for use in building construction. Martínez-Lage et al.
19 [21] likewise observed a decline in compressive strength equal to the RMA replacement ratio (30 %). In
20 contrast, Mas et al. [28] reported that in concretes manufactured with up to 25 % replacement,
21 compressive and tensile strength were just ≤ 15 % lower than in conventional concrete.
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23 The cement industry, in turn, has spied an opportunity in C&DW valorisation as additions, another
24 innovative line of international research that has been scantily exploited to date. The present authors
25 found that new cements containing 10 % or 20 % C&DW exhibited optimal calorimetric and rheological
26 performance. In a similar vein, Asensio et al. [5, 32, 33] assessed the durability, strength and calorimetric
27 behaviour of cements containing 10 % to 30 % ceramic waste. Their satisfactory results served as a
28 basis for the award of two patents [34, 35].
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30 Moreover, in recent years the desire to improve the performance of recycled aggregate concrete has
31 driven interest in the effect of the simultaneous use of supplementary cementitious materials (SCMs)
32 such as fly ash (FA), silica fume (SF) and granulated blast furnace slag (GGBS), and RCA [36, 37]. The
33 growing use of SCMs has encouraged some researchers to seek new, more economically sustainable
34 sources of such materials. Some have studied the joint use of thermally activated cement dust [38] or
35 even ground brick [39] with aggregate produced by crushing concrete debris. The findings showed that
36 20 % RCA and 5 % thermally activated cement [38] or 30 % RCA and 15 % ground brick can be used
37 simultaneously with no significant loss in later age concrete mechanical strength [39].
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39 The originality of the present study lies in the exploration of the simultaneous valorisation of C&DW as
40 coarse recycled mixed aggregate and its ceramic fraction as an SCM, an unprecedented approach that
41 would fuel scientific progress and constitute a major advance in the management and valorisation of
42 such waste. Specifically, it analyses the effect of the joint use of cement with 25 % ceramic C&DW [34]
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and RMA from C&DW to partially (25 % and 50 %) replace the natural coarse aggregate in structural concrete. Fresh concrete consistency, entrained air and bulk density, along with hardened concrete colour, bulk density and compressive, tensile and flexural strength are determined. A UNIANOVA is applied to the findings to assess the effect of RMA percentage and cement type and a combination of the two on the response variables analysed.

2. Materials and Methods

2.2. Materials

2.2.1. Cement

The concretes were manufactured with 100 % conventional 42.5 R unadditioned portland cement (CEM I 42.5 R) supplied by a Lafarge Holcim group cement plant located in the Spanish province of Toledo or with 75 wt% of that cement and 25 wt% of the ceramic fraction of construction and demolition waste (CEM-25CDW). The latter product, classifiable as 42.5 MPa CEM II/B or CEM/IV cement, is registered under patent No. ES2512065.

Further to the data on compressive strength of the mortars made with these cements shown in **Error! Reference source not found.**, both binders met the mechanical strength requirements laid down in European standard EN 197-1 [40] for 2 d and 28 d 42.5 R cements. The figure also shows that strength gain was slower in the new than in the conventional cement due to the pozzolanicity of the addition, studied by Asensio et al. [5, 41].

Figure 1. Mechanical strength of the cements used in concrete preparation

Both binders also met the sulfate, chloride and insoluble residue content, loss on ignition, soundness and initial setting time requirements established in EN 197-1 [40].

2.2.2. Superplasticiser

BRYTEN NF, a modified water-base polycarboxylate superplasticiser furnished by FUCHS Lubricantes, was added to the mixes.

2.2.3. Aggregates

The recycled aggregate was supplied by a C&DW processing plant in Extremadura (western Spain). The two fractions supplied, 12/22 mm and 6/12 mm, were respectively labelled RMA-1 and RMA-2. The natural crushed siliceous aggregate consisted in three particle size fractions: natural sand (NS, 0/6 mm), gravel 1 (NG-1, 12/22 mm) and gravel 2 (NG-2, 6/12 mm).

Figure 2. Particle size distribution of coarse aggregates and EN 12620 [42] -allowable ranges for use in concrete

The coarse aggregate particle size distributions and the maximum and minimum ranges set out in European standard EN 12620 [42] for concrete aggregate are shown in **Error! Reference source not found.** All the materials used were well graded and lay within the particle size ranges recommended in EN 12620 [42] for coarse aggregate with maximum sizes of 20 mm or 10 mm. The practically identical

particle size distribution in the natural and recycled aggregates ensured that as the granular skeleton would not be modified, it would have no differential effect on end concrete performance.

Error! Reference source not found. lists the physical and mechanical properties of the coarse recycled aggregates and the provisions in EN 12620 [42] and Spanish structural concrete code EHE-08 [17] on aggregate used in concrete manufacture. The recycled aggregates had lower saturated surface dry density (SSDD) and higher absorption values than natural aggregates NG-1 and NG-2, due primarily to the presence of bound mortar and ceramic materials. Absorption was 5.27 % for RMA-1 and 6.28 % for RMA-2, both higher than the 5 % ceiling laid down in EN 12620 [42] and EHE-08 [17] for concrete aggregate. The Los Angeles coefficient values, at 32 % for RMA-1 and 36 % for RMA-2, were higher than the 15 % to 18 % range in the natural aggregate, likewise due to the bound mortar and ceramic fraction comprising the RMA, which rendered them more brittle. These values were nonetheless below the 40 % ceiling established in EHE-08 [17] and EN 12620 [42] for use in concrete. The flakiness index was higher, at 21 % to 25 %, in the natural aggregate than in the RMA (10 %), although this property is not a boundary condition for using aggregate in concrete manufacture [17, 42]. The composition of RMA-1 and RMA-2 consisted in >87 % unbound concrete and aggregate, <7 % ceramic (Rb) material and <1 % minority components such as bituminous matter, gypsum and floating particles. In light of that composition, further to EHE-08 [17] the recycled aggregates would be classified as recycled mixed aggregate with an Rb content of over 5 %

Table 1. Physical and mechanical properties of the aggregates

2.3. Sample preparation

The concretes were prepared as summarised in the flowchart in **Error! Reference source not found.**. Six mixes were prepared: i) conventional concrete with portland cement and natural aggregate (CC); ii) concrete with portland cement and 25 % recycled mixed aggregate (CR-25); iii) concrete with portland cement and 50 % recycled mixed aggregate (CR-50); iv) concrete with recycled cement and natural aggregate (CR-R); v) concrete with recycled cement and 25 % recycled mixed aggregate (CRR-25); and vi) concrete with recycled cement and 50 % recycled mixed aggregate (CRR-50).

The mixes were batched to the British method [46], which defines the starting data as: 28 d concrete characteristic strength (f_{ck})=30 MPa; cement strength class= 42.5 R; w/c ratio=0.45; and maximum aggregate size=20 mm. As the batching proportions in **Error! Reference source not found.** show, all the mixes had a constant (w/c)_{effective} to ensure comparability of concrete properties.

Figure 3. Experimental programme

Table 2. Concrete mixes

2.2 Test methodology

Each fresh concrete was analysed to European standards for density (EN 12350-6 [47]) air content (EN 12350-7 [48]) and workability (EN 12350-2 [49]). The hardened materials were tested for density (EN 12390-7 [50]), compressive strength (EN 12390-3 [51]), tensile strength (EN 12390-6 [52]), bending strength (EN 12390-5 [53]) and colour. The colour parameters were quantified on a Minolta CM-2500d portable spectrophotometer designed to determine the L*a*b* colour space (L* = lightness and a* and

b* = colour coordinates), first defined by the International Commission on Illumination (CIE) (Commission Internationale de l'éclairage) in 1976 [54].

Three specimens were prepared per mix and test age for each trial: for compressive strength, 150 mm cubes; for flexural strength, 100x100x400 mm prisms; and for tensile strength, 150 mm diameter, 300 mm high cylinders. The specimens were cured at 20 °C for the first 24 h and then under water at 20±2 °C until tested. The samples were prepared to European standard EN 12390-1 [55] and EN 12390-2 [56] recommendations.

2.4. Statistical analysis

Regression analysis and analysis of variance (UNIANOVA) were performed to determine whether the percentage of RMA and cement type or their interaction had a statistically significant effect on the response variables. Here the response variables at each curing age were: fresh concrete workability, density and air content; and hardened concrete density and compressive, tensile and flexural strength. Compressive strength was determined at 7 d, 28 d, 90 d, 180 d and 365 d and density and splitting tensile and flexural strength at 28 d and 90 d. All the response variables were tested for normal distribution and homoskedacity prior to running the UNIANOVA [57]. IBM SPSS software, version 22, was used for the statistical tests, in which a 95 % confidence level was adopted.

3. RESULTS AND DISCUSSION

3.1. Properties of fresh concrete

3.1.1. Workability

Mix workability was unaffected by the inclusion of RMA, either alone or with recycled cement. The slump data recorded for all the concretes ranged from 11 cm to 13 cm, values compliant with the fluid consistency (10 cm to 15 cm) defined by EHE-08 [17] and the S3 requirement laid down in European standard EN 206-1 [58].

The UNIANOVA findings on the effect of %RMA and cement type on concrete workability showed that neither factor separately nor their interaction had a statistically significant effect on that parameter (p-value>0.05). Those results were consistent with the patterns recorded by Medina et al. [24] for <50 % recycled mixed aggregate and Barbudo et al. [59] for <100 % recycled concrete aggregate, in which the use of recycled aggregate had no significant effect on the workability of concretes prepared with a constant effective w/c ratio.

3.1.2. Bulk density and air content

The plots of bulk density and air content against the percentage of recycled mixed aggregate in concretes made with CEM I or CEM-25CDW showed the relationships to be linear (Figure 4). Both properties were directly related to the RMA content, with correlation coefficients of $R^2>0.92$ for density and $R^2>0.84$ for air content. The decline in density and rise in air content were due to the lower density (Table 1) and higher porosity [22, 60] of the recycled mixed aggregate.

Figure 4. Air content (A_c) and fresh bulk density (ρ_{fresh}) vs recycled aggregate content (X_{RMA}) in conventional and recycled cement concretes

The UNIANOVA results for the effect of %RMA and cement type on density and air content are given in Table 3. The percentage of RMA accounted for 67 % of the variation in density, cement for 25 % and their interaction for a marginal ≈ 4 %. That marginality was consistent with the lack of statistical significance of the effect of the recycled cement-RMA combination on density ($p\text{-value} > 0.05$). The findings also showed that cement type had no significant effect on concrete density, in keeping with results reported by Ge et al. [61] for conventional concretes prepared with ≤ 40 % ground brick.

Table 3. Results of UNIANOVA for workability, bulk density and air content in fresh concrete

The statistical test for air content exhibited a pattern similar to that observed for density, inasmuch as the two properties are directly related. The RMA accounted for 33 % of the variation in this property and cement type for 15 %. The combination of the two factors had no statistically significant effect on air content ($p\text{-value} > 0.05$), contributing, like density, only marginally to variation.

3.2. Properties of hardened concrete

3.2.1. Bulk density

Hardened concrete bulk density is plotted against the replacement ratio and cement type for the 28 d and 90 d materials in Figure 5. Density declined linearly ($R^2 > 0.95$) with rising RMA content, irrespective of the type of cement used to prepare the concretes. That decline was primarily attributable to the lower density of recycled than conventional aggregate (**Error! Reference source not found.**). The pattern observed was consistent with the bulk density findings for fresh concrete (item 3.1.2) and the results reported by Matías et al. [12] for RCA and Beltrán et al. for RMA [62] for concretes.

Figure 5. Bulk density versus RMA (X_{RMA}) content in 28 d and 90 d concretes made with conventional and recycled cement

In the 28 d OPC concretes, density was 2 % lower in CR-25 and 3 % lower in CR-50 than in CC. In the recycled cement concretes, 28 d density was 1 % lower in CR-R, 3 % lower in CRR-25 and 4 % lower in CRR-50 than in CC. Those values lay within the 2 % to 4 % range observed by Mas et al. [28] and López-Uceda et al. [29] in concretes made with up to 40 % RMA. The differences in density between the concretes with CEM I and the respective materials with CEM-25CDW was never in excess of 2 %.

The 90 d bulk density values for all the concretes was practically the same as the 28 d values, with variations of ≤ 1 %. The figure nonetheless shows that the difference was greater in the concretes with CEM-25CDW due to the pozzolanicity of the ceramic C&DW comprising the SCM.

The UNIANOVA results for the effect of %RMA and cement type on concrete bulk density (Table 4) showed that here also the factor with the greatest impact was RMA (80 % of the variation) at both ages, followed by cement type (< 20 % of the variation) and the interaction between the two (< 5 % of the variation). The effect of cement type declined with rising curing time due to the intrinsic properties of cement CEM-25CDW. Each factor separately had a statistically significant effect ($p\text{-value} < 0.05$) on density, whereas their interaction did not ($p\text{-value} > 0.05$).

Table 4. UNIANOVA results for bulk density

The portland cement concrete density/recycled cement concrete density ratio is plotted against the percentage of RMA in Figure 6. The linear relationship ($R^2=0.98$) attested to the similarity of the behaviour in the two variables with rising RMA content (Equation 1):

$$\rho_{CEM-25CDW} = \frac{\rho_{CEMI}}{1.1079 + 0.0003X_{RMA}(\%)} \quad (1)$$

where: $\rho_{CEM-25CDW}$ is recycled cement density in Mg/m^3 , ρ_{CEMI} conventional cement concrete density in Mg/m^3 and X_{RMA} recycled mixed aggregate content in percentage (%).

Figure 6. Portland cement concrete bulk density/recycled cement concrete bulk density versus RMA content (X_{RMA})

3.2.2. Compressive strength

The mean 7 d (f_{cm7}), 28 d (f_{cm28}), 90 d (f_{cm90}) and 365 d (f_{cm365}) compressive strength values are given in Table 5. Mean 28 d (f_{cm28}) compressive strength was greater than the 30 MPa characteristic strength, irrespective of cement type and percentage of recycled mixed aggregate.

Table 5. Compressive strength values by age ($\pm$ standard deviation)

The inclusion of RMA (CR-25 and CR-50) induced no significant difference in 28 d strength relative to CC. That was because the new recycled mixed aggregate constituent (ceramic materials, concrete...)/paste interfaces (ITZs) were similar to the natural aggregate/paste ITZs (see section 3.3), an observation reported by other authors [13, 63, 64].

In the concrete with CEM-25CDW cement (CR-R), 28 d strength was 10 % lower than in concrete with CEM I. That decline was smaller than the 14 % reported by Subasi et al. [65], who added 20 % ceramic waste as a filler in self-consolidating concretes.

The simultaneous use of CEM-25CDW and RMA (CRR-25 and CRR-50) induced declines of 11 % to 20 % relative to CC. Those values lay within the 11 % to 33 % range observed by Letelier et al. [38, 39] in concretes to which 5 % to 15 % thermally activated recycled cement and 20 % to 40 % RCA [38] or 15 % recycled ground brick and 30 % RCA [39] were simultaneously added.

Figure 7. Compressive strength in concretes made with CEM I cement relative to their respective 28 d values, by age

Compressive strength by age relative to each concrete's 28 d value is shown in Figure 7 for the CEM-I family and in Figure 8 for the CEM-25CDW family. Compressive strength rose with curing time in both the concretes made with recycled cement (CR-R, CRR-25 and CRR-50) and those prepared with conventional cement (CC, CR-25 and CR-50). The inclusion of recycled aggregate consequently had no effect on concrete hardening. The recycled cement concretes exhibited lower relative strength at 7 d and higher values at >90 d than the conventional cement concretes. Those findings were closely related to the intrinsic properties of the new cement, for its 25 % ceramic waste component was characterised by high late age pozzolanicity (see item 2.2.1).

The 7 d CEM I concretes with 25 % RMA exhibited 86 % of the strength of their 28 d value, and those with 50 % RMA, 83 %. Those values were consistent with the 75 % to 90 % reported by Bravo et al. [66] for concretes with up to 50 % recycled C&DW aggregate sourced from different recycling plants in Portugal. Strength in the 7 d concrete with recycled cement (and natural aggregate) was 84 % of its 28 d value, only slightly lower than the 93 % recorded for conventional concrete. Concrete strength in 7 d CRR-25 was 77 % of its 28 d value and in CRR-50 66 %. Those numbers, also lower than observed in the respective materials with conventional cement, lay within the 66 % to 71 % range observed for concretes with 25 % and 35 % fly ash and 20 % to 50 % recycled concrete aggregate [37].

Late age strength followed a different pattern than observed for the 7 day findings. In the 365 d materials, the greatest rises were found in concretes containing both recycled cement and RMA: in mix CRR-25 strength was 25 % and in CRR-50 37 % higher than their 28 d values. Strength rose less steeply in the CEM-I mixes, with CR-25 13 % higher and CR-50 17 % higher than their 28 d strength values.

Figure 8. Compressive strength in concretes made with CEM-25CDW cement relative to their respective 28 d values, by age

The 365 d mix made with CEM-25CDW and natural aggregate (CR-R) exhibited a 25 % rise over its 28 d strength, 6 points higher than observed for the control mix (CC). The greater rise in performance with curing age in the concretes with the new recycled cements (CR-R, CRR-25 and CRR-50) than in the concretes with conventional cement (CC, CR-25 and CR-50) was directly related to the intrinsic properties of the former, as discussed earlier. This behaviour was consistent with the what Kannan et al. [67] and Ge et al. [61] observed in concretes containing 10 % to 40 % roof tile or brick waste in the stead of portland cement. Those authors reported that strength rose more with curing time in the new concretes than those made with conventional cement, due to the pore system refinement induced by the late age pozzolanicity exhibited by the waste.

The UNIANOVA results on the effect of %RMA and cement type on concrete compressive strength are listed in Table 6. The factor with the greatest effect on compressive strength was cement type, accounting for over 60 % of the variation in all the ages studied, followed by percentage of RMA (22 %) and the combination of the two (7 %). Nonetheless, although the recycled cement (CEM-25CDW) was the factor that impacted compressive strength the most, the decline in strength was never observed to exceed 29 % (value for 7 d concretes with 50 % RMA) relative to the respective concretes with conventional cement. The difference narrowed to 5 % at 365 d, a value much lower than the SCM replacement ratios involved. The declining percentage of the contribution of the cement to the variation in the dependent variable was a further indicator of that fact (see Figure 9). At later ages, then, compressive strength in the new concretes with both recycled cement and RMA was comparable to conventional concrete strength.

Table 6. UNIANOVA results for compressive strength

Figure 9. Contribution of factors and their interaction to variation in compressive strength

3.2.3. Relationship between portland and recycled cement compressive strength

The ratio between mean 28 d compressive strength of CEM I and CEM-25CDW is plotted against RMA content in Figure 10 (Equation 2). At 0.95, the determination coefficient (R^2) was indicative of a close relationship between the two strengths and their linearity with the percentage of RMA.

$$f_{cm28,CEM-25CDW} = \frac{f_{cm28,CEMI}}{1.102 + 0.002X_{RMA}(\%)} \quad (2)$$

Figure 10. 28 d portland cement compressive strength/28 d recycled cement compressive strength ratio versus percentage of RMA

where: $f_{cm28,CEM-25CDW}$ is 28 d recycled cement compressive strength in MPa, $f_{cm28,CEMI}$ 28 d conventional cement compressive strength in MPa and X_{RMA} recycled mixed aggregate content in percentage (%).

3.2.4. Splitting tensile strength

The 28 d and 90 d splitting tensile strength findings (f_{st}) are shown in **Error! Reference source not found.**figure 11, along with the linear regression between performance and replacement ratio. Strength declined with rising RMA content in all the concretes, irrespective of cement type and age. The same pattern was observed by Evangelista and Brito [68] for recycled concrete aggregate and Yang et al. [69] for recycled mixed aggregate concretes. Both reported that the decline in strength was due in particular to the greater porosity in the recycled aggregate.

Figure 11. 28 d and 90 d splitting tensile strength versus RMA content in concretes made with conventional and recycled cement

In the 28 d concretes, tensile strength relative to CC was 3 % lower in CR-25, 10 % lower in CR-50 and in the concrete with the new recycled cement (CR-R), 5 % lower. The decline was slightly steeper when both recycled cement and RMA were used: 23 % in CRR-25 and 25 % in CRR-50. These findings were consistent with the results observed by Kou et al. [37] who, using concretes with the same amount of cement and the same w/c ratio as in this study, found that tensile strength declined by 8 % to 36 % in concretes with 20 % to 35 % fly ash and 20 % to 50 % recycled concrete aggregate.

In 90 d CR-25, tensile strength was 9 % higher and in CR-50, 10 % higher than their respective 28 d values. Combining recycled cement and RMA yielded 7 % higher 90 d than 28 d strength in CRR-25 and 29 % higher in CRR-50. That rise in tensile strength with curing age in concretes with recycled cement was consistent with earlier observations [36] for concretes with different mineral additions (35 % fly ash, 15 % metakaolin, 10 % silica fume) and 50 % RCA relative to conventional cement concretes bearing 50 % RCA.

Irrespective of age, the decline recorded relative to the reference concrete was consistently smaller than the RMA replacement ratio. That behaviour may be explained by: i) the similarity in the properties of the RMA/paste and natural aggregate/paste ITZs [63, 70]; and ii) the presence of micro cracks in the recycled aggregate which would partially offset the lower resistance to tensile stress [71].

The UNIANOVA results for tensile strength in Table 7 show that %RMA and cement type were the factors with the greatest effect on that parameter. The RMA contributed 30 % to the 28 d variation and cement type 36 %, whilst in the 90 d concretes RMA accounted for 43 % and cement type for 28 %. Cement type was the primary determinant in 28 d tensile strength, whereas in the 90 d materials the percentage of RMA prevailed, as in compressive strength. That reversal was attributed to the pozzolanicity of the ceramic waste in the C&DW used to manufacture the recycled cement, a finding reported earlier by Asensio et al. [41] and Medina et al. [72]

Table 7. UNIANOVA results for tensile strength

The interaction between cement type and percentage of RMA showed no statistically significant effect on tensile strength ($p\text{-value} > 0.05$), with a $p\text{-value}$ of 0.17 at 28 d and of 0.75 at 90 d.

The factor with the heaviest impact in both families, CEM I (CC, CR-25 and CR-50) and CEM-25CDW (CR-R, CRR-25 and CRR-50), was %RMA, although the contribution of this factor was 1.3 times greater in the latter than in the former, as Figure 11 shows.

3.2.5. Flexural strength

The 28 d and 90 d flexural strength (f_{fl}) values for the concretes are charted in Figure 12. As in the other mechanical properties, a linear correlation was observed between the parameter and the RMA content, although R^2 was smaller than observed for compressive strength. These findings concurred with the results observed in earlier studies [38, 73-75], according to which flexural strength was less affected by the amount of recycled aggregate than compressive and tensile strength.

Figure 12. 28 d and 90 d flexural strength versus RMA content (X_{RMA}) in concretes made with conventional and recycled cement

CR-25 exhibited 6 %, CR-50 10 % and CR-R 11 % lower 28 d strength than CC. Those values lay within the 5 % to 15 % found by Bravo et al. [66] for concretes with 25 % to 50 % recycled aggregate with a composition similar to that used in this study. Concrete CRR-25 had 14 % and CRR-50 17 % lower strength than CR-R. Those values compared to the 10 % to 14 % observed for concrete made with 20 % to 40 % RCA and concrete manufactured with 15 % thermally activated cement powder [38]. They were similar to the ≈ 17 % recorded by Letelier et al. [39] for concretes made with 15 % recycled ground brick and 30 % RCA.

The concretes prepared with conventional cement (CC, CR-25 and CR-50) exhibited 90 d flexural strength values similar to those observed in the 28 d materials (Figure 12). In the concretes with recycled cement (CR-R, CRR-25 and CRR-50), however, strength rose with age by 2 % to 11 %, ultimately reaching values similar to those recorded for concretes made with CEM I. Those findings were consistent with the greater rises in compressive and tensile strength with curing age in the mixes made with recycled cement (CEM-25CDW) than in those with conventional cement (see items 3.2.3 and 3.2.5).

The UNIANOVA values for flexural strength given in Table 8 varied depending on curing age. In the 28 d concretes, the most significant factor was cement type, accounting for 35 % of the variation,

compared to 19 % for percentage of RMA. The interaction between cement type and percentage of RMA had no statistically significant effect (p-value= 0.54) on flexural strength.

Table 8. UNIANOVA results for flexural strength

In the 90 d materials, the factor carrying the greatest weight was percentage of RMA (38 % variation), whilst cement type was not statistically significant (p-value=0.73). These findings corroborated the significant improvement in 90 d flexural strength in concretes made with recycled cement, with values comparable to those for concretes made with conventional cement.

Analysing the results by families revealed differences between %RMA and curing age depending on the cement used. Curing age was significant for family CEM-25CDW but not for family CEM I (p-value>0.05). Further attesting to a slower strength gain than in the conventional concrete due to the pozzolanicity of the new addition.

3.3. Compliance

The 28 d splitting tensile (f_{st}) and flexural (f_{fl}) strength values for the recycled concretes are shown in Figure 13, along with the values estimated with Equation 3 for the former and Equation 4 for the latter, recommended in both EHE-08 [17] and EC-2 [76]:

$$f_{ctm} = 0.30 \cdot \sqrt[3]{f_{ck}^2} \quad (3)$$

$$f_{ctm,fl,est} = f_{ctm} \times (1.6 - h / 1000) \quad (4)$$

Figure 13. Experimental and EHE-08[17]/EC-2[76] theoretical tensile and flexural strength of the concretes studied

where: f_{ctm} is the theoretical tensile strength as per EHE-08/EC-2, f_{ck} is mean 28 d compressive strength found by applying a factor of 0.90 to convert cubic to cylindrical specimens further to EHE-08 [17] recommendations, $f_{ctm,fl,est}$ is theoretical flexural strength as per EHE-08/EC-2 and h is the height of the sample tested (see section 2.2).

With the exception of CRR-25, in which it was slightly lower, experimental was greater than theoretical tensile strength in all the concretes. In the CEM I family, strength was 1 % to 7 % higher than the theoretical value in the RMA concretes and in the CEM-25CDW family, likewise with RMA, from 1 % to 11 % higher. Mix CR-R exhibited the highest strength relative to the theoretical value, at 11 %, higher also than the 10 % recorded for its analogue, the reference concrete (CC).

The pattern for flexural strength was similar, with higher experimental than the theoretical values found with the expression for conventional concretes. Specifically, in the CEM I family with RMA, the rise ranged from 8 % to 9 % and in the CEM-25CDW family with recycled aggregate, from 7 % to 12 %.

The above findings showed that the equations proposed in EHE-08 and EC-2 are apt for predicting flexural strength in all these concretes. In contrast, in the RMA concretes, with or without recycled cement, the theoretical tensile strength equations did not correctly predict behaviour. Rather, a

correction factor of 0.85 had to be applied to the EHE-08/EC-2 equation to accommodate the combined effect of the two new materials.

Figure 14. a) Concrete with 50 % RMA (CR-50); b) concrete with recycled cement and 50 % RMA (CRR-50)

(**Note:** **Rn**: natural aggregate; **Ru**: unbound aggregate; **Rb_a**: sanitary ware waste; **Rb_b**: crushed brick; **Rb_c**: crushed roof tile; and **Rc**: concrete aggregate)

3.4. Morphological analysis

Further to the enlarged photos of the cross-sections (Figure 14) of concretes CR-50 (Figure 14a) and CRR-50 (Figure 14b), the natural aggregate and the components of the recycled mixed aggregate were distributed uniformly in the cementitious matrix, whilst the two materials varied in colour (see section 3.5). The figure also shows the RMA/paste ITZ for some of the components, according to which they bonded effectively to the matrix, irrespective of cement type (CEM I or CEM-25CDW). No significant differences were perceptible between natural aggregate/paste and RMA component/paste ITZ thickness. That was consistent with earlier reports by authors deploying nanoindentation to study the micro-elastic properties and thickness of the ITZs between paste and ceramic sanitary ware [63], ceramic block [64] and concrete waste [64]. Their observations were likewise consistent with the macroscopic behaviour recorded here.

3.5. Colour

Micrographs showing the colour of CEM I and CEM-25CDW concretes are reproduced in Figure 15a and their colour coordinates in Figure 15b. The colour coordinate ranges ($a^* = 0-0.9$ and $b^* = 4.0-5.6$) lay in the grey zone [77]. The inclusion of ceramic waste such as roof tile and block as SCMs in the cement induced a rightward (i.e., redward) shift in the $+a^*/+b^*$ axis relative to the CEM I concretes. Similar, albeit smaller, shifts were reported by other authors assessing the effect on these properties in mortars made with cements bearing industrial waste such as paper sludge [78] or coal tailings [79].

Figure 15. Concrete colour: a) micrographs; b) coordinates a^* and b^*

The use of CEM-25CDW lowered the lightness (L^*) value in these concretes to $\approx 68\%$, compared to $\approx 77\%$ in the CEM I materials.

That change in colour added value to this new cement, for the resulting rusticity made it ideal for concrete elements, particularly in building construction where colour or a lower visual impact with natural or rural surrounds may be design requisites.

4. CONCLUSIONS

The conclusions to be drawn from the present study are as follows.

- Neither RMA nor cement type had a statistically significant effect on concrete workability.
- The 2 % to 5 % decline in density and rise in entrained air in the concretes were primarily accounted for by the percentage of RMA. Cement type made no statistically significant contribution to the variation in those properties.

- Late age mechanical performance was similar in concrete bearing recycled cement and material made with conventional cement.
- Compressive strength was affected primarily by the type of cement used. Concretes with recycled cement and RMA exhibited 10 % to 20 % lower 28 d strength than concrete made with conventional cement. That decline narrowed with curing time, to 5 % to 7 % in 365 d concretes made with CEM-25CDW and 50 % RMA.
- The interaction between recycled cement and RMA had no significant impact on concrete tensile or flexural strength. The declines in strength observed in concretes CR-R, CRR-25 and CRR-50 were attributable to the separate action of the two factors.
- The presence of recycled cement was the determinant in 28 d tensile and flexural strength. In the 90 d materials, however, the percentage of RMA was the prevailing factor.
- The effect of cement type on the properties analysed declined with concrete curing age.
- The equations proposed by EHE-08 and the Eurocode for estimating flexural strength proved to be apt for these new concretes. The expression for estimating tensile strength in those two codes had to be corrected by a factor of 0.85, however, to accommodate the effect of RMA, with or without cement CEM-25CDW.
- The use of CEM-25CDW induced a rightward shift in the colour coordinates (red scale) and a 12 % decline in lightness relative to CEM I.

In light of the present findings, construction and demolition waste can be used simultaneously as supplementary cementitious materials (25 %) and coarse aggregate (<50 %) in structural concrete for both civil and building construction applications requiring a characteristic compressive strength of 30 MPa. Such joint valorisation of C&DW as SCMs and coarse aggregate would help mitigate the worldwide environmental problem generated by such waste and contribute to CO₂ emissions abatement by lowering the construction industry's demand for conventional portland cement and natural aggregate.

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Figure 1. Mechanical strength of the cements used in concrete preparation

Figure 2. Particle size distribution of coarse aggregates and EN 12620 [42]

Figure 3. Experimental programme

Figure 4. Air content (Ac) and fresh bulk density (ρ_{fresh}) vs recycled aggregate content (X_{RMA}) in conventional and recycled cement concretes

Figure 5. Bulk density versus RMA (X_{RMA}) content in 28 d and 90 d concretes made with conventional and recycled cement

Figure 6. Portland cement concrete bulk density/recycled cement concrete bulk density versus RMA content (X_{RMA})

Figure 7. Compressive strength in concretes made with CEM I cement relative to their respective 28 d values, by age

Figure 8. Compressive strength in concretes made with CEM-25CDW cement relative to their respective 28 d values, by age

Figure 9. Contribution of factors and their interaction to variation in compressive strength

Figure 10. 28 d portland cement compressive strength/28 d recycled cement compressive strength ratio versus percentage of RMA

Figure 11. 28 d and 90 d splitting tensile strength versus RMA content in concretes made with conventional and recycled cement

Figure 12. 28 d and 90 d flexural strength versus RMA content (X_{RMA}) in concretes made with conventional and recycled cement

Figure 13. Experimental and EHE-08 [17]/EC-2 [76]

Figure 14. a) Concrete with 50 % RMA (CR-50); b) concrete with recycled cement and 50 % RMA (CRR-50)

(Note: Rn: natural aggregate; Ru: unbound aggregate; Rb_a: sanitary ware waste; Rb_b: crushed brick; Rb_c: crushed roof tile; and Rc: concrete aggregate)

Figure 15. Concrete colour: a) micrographs; b) coordinates a^* and b^*

Table 1. Physical and mechanical properties of the aggregates

Property [Standard]	Aggregate					
	NS	NG-1	NG-2	RMA-1	RMA-2	EN-12620 [42]
SSDD (Mg/m ³) [43]	2.76	2.74	2.74	2.45	2.42	-
Absorption coefficient (wt%) [43]	1.18	0.78	0.88	5.27	6.28	<5%
Los Angeles coefficient (wt%)[44]	-	18	16	36	32	40
Flakiness index (wt%) [45]	-	25	21	10	10	35

Table 2. Concrete mixes

Mix	Material (kg/m ³)								
	NS	NG-1	NG-2	RMA-1	RMA-2	Cement	Water	SP	(w/c) ^{effective}
CC	732.36	766.69	382.96	-	-	400.00	193.03	6.20	0.45
CR-25	720.79	565.94	282.69	182.80	90.75	400.00	202.08	6.20	0.45
CR-50	705.38	369.22	184.43	357.77	177.62	400.00	210.63	6.20	0.45
CR-R	732.36	766.69	382.96	-	-	400.00*	193.03	6.20	0.45
CRR-25	720.79	565.94	282.69	182.80	90.75	400.00*	202.08	6.20	0.45
CRR-50	705.38	369.22	184.43	357.77	177.62	400.00*	210.63	6.20	0.45
Note. - * Mix prepared with CEM-25CDW									

Table 3. Results of UNIANOVA for workability, bulk density and air content in fresh concrete

Control factor	Bulk density (ρ_{fresh})		Air content (Ac)	
	p-value ^a	Contribution (%)	p-value ^a	Contribution (%)
RMA (%)	0.00	67.10	0.05	32.90
Cement type	0.00	25.70	0.08	15.10
RMA (%) x cement type	0.14	3.70	0.76	2.30
Note. - ^a confidence level ≥ 95 %				

Table 4. UNIANOVA results for bulk density

Factor	28 d bulk density		90 d bulk density	
	p-value ^a	Contribution (%)	p-value ^a	Contribution (%)
RMA (%)	0.00	78.80	0.00	80.37
Cement type	0.00	19.04	0.00	11.74
RMA (%) x cement type	0.50	0.00	0.04	3.04
Note. - ^a confidence level ≥ 95 %				

Table 5. Compressive strength values by age ($\pm$ standard deviation)

Concrete	Compressive strength, f_{cm} (MPa)			
	$f_{cm,7}$	$f_{cm,28}$	$f_{cm,90}$	$f_{cm,365}$
CC	47.78 $\pm$ 0.02	51.17 $\pm$ 0.18	56.96 $\pm$ 1.01	60.93 $\pm$ 1.16
CR-25	44.24 $\pm$ 0.22	51.69 $\pm$ 0.65	57.51 $\pm$ 0.56	58.53 $\pm$ 0.28
CR-50	42.70 $\pm$ 0.45	51.17 $\pm$ 0.58	53.19 $\pm$ 0.33	59.65 $\pm$ 0.23
CR-R	38.65 $\pm$ 0.65	46.06 $\pm$ 0.60	51.83 $\pm$ 0.69	57.79 $\pm$ 0.62
CRR-25	35.25 $\pm$ 0.30	45.71 $\pm$ 1.41	47.87 $\pm$ 0.49	57.00 $\pm$ 0.94
CRR-50	30.38 $\pm$ 0.73	41.18 $\pm$ 0.10	47.52 $\pm$ 1.06	56.41 $\pm$ 0.43

Table 6. UNIANOVA results for compressive strength

7 d compressive strength					
Factor	Df	Sum of squares	Variance	F ^a	p-value ^a
RMA (%)	1	133.81	66.90	204.96	0.00
cement type	2	463.20	463.20	87504.38	0.00
RMA (%) x cement type	2	10.62	5.31	16.27	0.00
28 d compressive strength					
RMA (%)	1	24.71	12.35	15.61	0.00
cement type	2	222.25	222.25	280.93	0.00
RMA (%) x cement type	2	20.27	10.14	12.81	0.00
90 d compressive strength					
RMA (%)	1	49.35	24.67	26.62	0.00
cement type	2	208.83	208.83	250.65	0.00
RMA (%) x cement type	2	18.25	9.13	10.95	0.00
180 d compressive strength					
RMA (%)	1	1.37	0.68	0.76	0.00
cement type	2	87.10	87.10	96.92	0.49
RMA (%) x cement type	2	2.92	1.46	1.62	0.24
365 d compressive strength					
RMA (%)	1	8.74	4.37	5.85	0.02
cement type	2	31.26	31.26	41.82	0.00
RMA (%) x cement type	2	2.77	1.38	1.86	0.20
Note. - ^a confidence level ≥ 95 %					

Table 7. UNIANOVA results for tensile strength

28 d splitting tensile strength						
Factor	Df	Sum of squares	Variance	F ^a	p-value	Contribution (%)
RMA (%)	1	1.22	0.61	6.98	0.00	29.68
Cement type	2	1.47	1.47	16.90	0.00	35.92
RMA (%) x cement type	2	0.36	0.18	2.09	0.17	8.88
90 d splitting tensile strength						
RMA (%)	1	1.97	0.99	9.03	0.00	42.58
Cement type	2	1.29	1.29	11.77	0.01	27.73
RMA (%) x cement type	2	0.07	0.03	0.30	0.75	1.40
Note. - ^a confidence level ≥95 %						

Table 8. UNIANOVA results for flexural strength

28 d flexural strength						
Factor	Df	Sum of squares	Variance	F ^a	p-value	Contribution (%)
RMA (%)	1	0.79	0.40	2.75	0.10	19.01
Cement type	2	1.46	1.46	10.10	0.01	34.94
RMA (%) x cement type	2	0.19	0.94	0.65	0.54	4.51
90 d flexural strength						
RMA (%)	1	1.75	0.87	6.19	0.01	37.72
Cement type	2	0.02	0.02	0.12	0.73	0.37
RMA (%) x cement type	2	1.17	0.59	4.16	0.04	25.33

Note. - ^a confidence level $\geq 95\%$